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SHEAR STRUCTURAL RESPONSE OF DOUBLE LAP JOINTS FOR COMPOSITE PULTRUDED ELEMENTS

BY

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Abstract. This paper presents the outcomes of analytical and numerical investigations regarding the behavior of double lap shear joint composed of pultruded GFRP profiles and structural epoxy adhesive. The shear and the peeling stresses along the bond length have been evaluated and graphically plotted. Specific points at the top interface between the adhesive and the GFRP composite elements were established in order to closely record the stress and strain variations. The ultimate values and the patterns of the graphical distributions of the stresses indicates that the shear and the peeling stresses obtained by analytical methods are in good agreement with those calculated by numerical methods, except for the peak values near the free edge of the bond length.

Keywords: adhesively bonded joints; double lap shear joint; finite element modelling; analytical model; GFRP composite elements.

1. Introduction

Fiber reinforced polymer (FRP) composite materials are increasingly being used in various engineering applications due to their unique set of

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mechanical and physical properties and also due to their superior characteristics when compared to the traditional materials. Some of the most important characteristics refer to: corrosion resistance, superior strength-to-weight ratio, magnetic neutrality and formability (Ţăranu *et al.*, 2013; Nimje *et. al.*, 2015). Regarding the joining methods of FRP composite elements, the most common ones that are currently utilised are: the mechanical fastening and the adhesive bonding. The mechanical fastening is easy to manufacture, simple to inspect and also offers the possibility of disassembling. But, one of the major disadvantages of this method refers to the necessity of drilling the FRP composite elements that are being assembled which usually leads to localized damages and stress concentrations (Adams & Wake, 1984). Thus, adhesively bonded connections have been found to be more convenient and adapted to the anisotropic behavior of FRP composite materials, allowing a smoother and more uniform stress transmission through the constituents.

There are two basic approaches for the structural analyzing of the adhesively bonded joints: the analytical and the numerical methods, respectively (Haghani, 2014). These two methods complement one another for design purposes. Closed-form (simplified) solutions are obtained through the analytical approach and may provide an estimation of the maximum values for stresses and strains which can be used in the preliminary design stages. They are also suitable for the selection of the appropriate adhesives and the joint geometric configuration. On the other hand, the available analytical models give close predictions only for specific bond configurations for which the failure pattern is controlled by the mechanical properties of the adhesive, being usually referred to as cohesive failures. When the FRP composite elements are adhesively joined in more complex geometries, the numerical approaches, usually based on the finite element method, give more accurate predictions in terms of stress and strain distribution along the bond length (Groll & Ţăranu, 2003; Keller & Vallee, 2005; Haghani, 2014).

This paper presents a comparative analysis of a double lap shear joint applied for three glass fibre reinforced polyester (GFRP) composite pultruded elements. The shear and the peeling stresses along the bond length are evaluated based on the existing analytical model (Hart-Smith, 1973) and by numerical approaches.

2. Properties of the Materials

The double lap shear joint analysed in this paper consists of GFRP composite elements produced by Fiberline and epoxy structural adhesive, Sikadur 30. The Fiberline GFRP composite profiles are made of E-glass fibers embedded in an isophthalic polyester resin. The fibrous reinforcement consists in unidirectional roving which are covered at both bottom and top sides by combined mats. The latter consist of woven mats 0°/90° as well as chopped strand mats, both stitched together (Valee *et al.*, 2009). The principal directions of the GFRP composite elements are illustrated in Fig. 1. The longitudinal direction is indicated as 0° and the transverse direction is indicated as 90°. The physical and the mechanical properties of the constitutive materials of the considered joints are given in Tables 1,...,4.

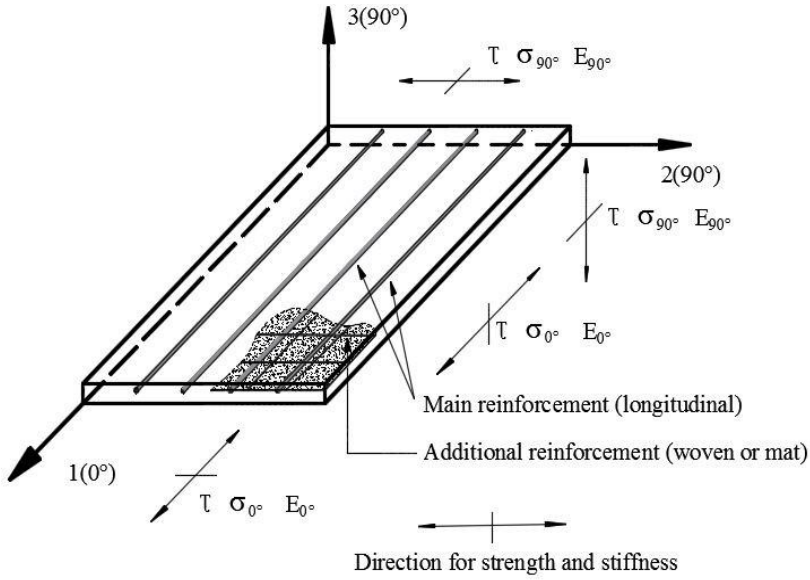


Fig. 1 – Indication of directions for strength and stiffness.

Table 1

Properties of the Adhesive (Sikadur 30 - Technical sheet, 2008)

Type	Density [kg/m^3] (mixed)	Compressive strength, $f_{c,a}$, [MPa]	Tensile strength, $f_{t,a}$, [MPa]	Modulus of elasticity, E_a, [GPa]
Sikadur 30	1,650	70,...,80	25,...,28	12.8

Table 2

Fiberline GFRP Composite Strip. Physical Characteristics

(Fiberline design manual, 2012)

Density [kg/m^3]	Operating temperature [ºC]	Fibre volume fraction [%]
1,500	–20 ~ +80	>60

Table 3
Fiberline GFRP Composite Strip. Typical Stiffness
(Fiberline design manual, 2012)

Longitudinal elasticity modulus [GPa]	Transverse elasticity modulus [GPa]	Shear modulus of elasticity [GPa]	Poisson's ratio, 0º, 90º	Poisson's ratio, 90º, 0º
23	8.5	3	0.23	0.09

Table 4
Fiberline GFRP Composite Strip. Mechanical Characteristics - Strength Values
(Fiberline design manual, 2012)

Tensile strength, 0º, [MPa]	Tensile strength, 90º, [MPa]	Compressive strength, 0º, [MPa]	Compressive strength, 90º, [MPa]
240	50	240	70

3. Model Geometry

The geometrical configuration of the model was designed so that the effect of peelings stresses upon the final bond strength is minimum. In order to obtain an accurate measurement and graphical representation of the stress distribution, the bond length was chosen greater than the effective one.

For the numerical model, specific points at the top interface between the adhesive and the GFRP composite elements were established in order to closely record the stress and strain variations. A total of 72 measuring points were assigned to the double lap joint model. The proposed configurations, the nominal dimensions of the specimen and the location of the probe measuring points are presented in Fig. 2.

4. Numerical Modelling

The specimen has been numerically modelled using ANSYS Workbench software. The numerical model consists in five parallelepiped shapes connected together to match the geometric configuration. A primitive parallelepiped shape is defined by eight nodes, each node having three degrees of freedom. For each node, the parameters of position and connectivity have been defined.

The final model has been meshed using triangular elements of 0.2 to 1 mm in size for the adhesive layer and rectangular elements of 1 to 3 mm for the adherents. The discretization details are presented in Fig. 3 and the loading scheme is depicted in Fig. 4.

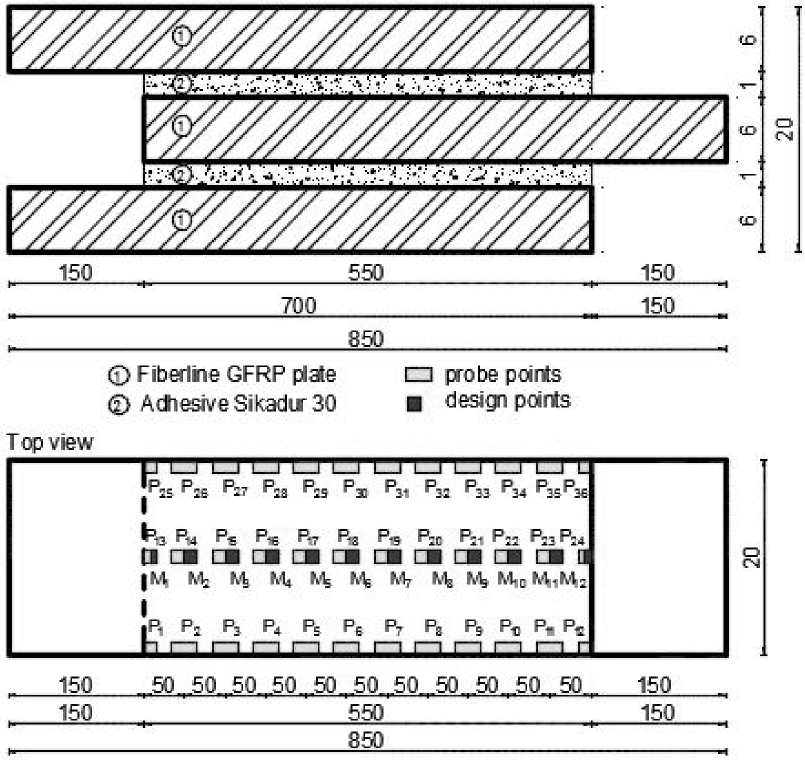


Fig. 2 – Double lap model geometry and the probe points.
Dimensions in mm (not at scale).

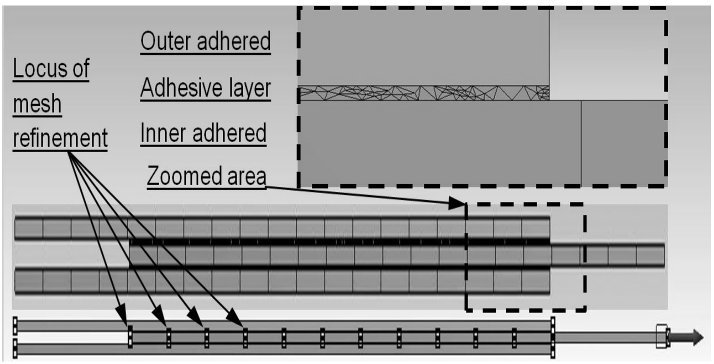


Fig. 3 – Meshing of the 3-D model.

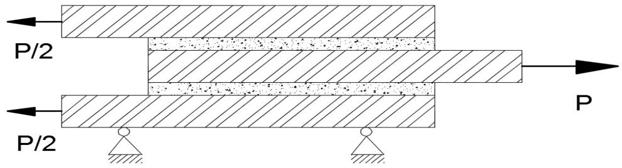


Fig. 4 – Loading scheme of the joint.

A refined mesh has been used for the overlap area. The refinement level has been set to 0.2, meaning that the maximum length of the triangular/rectangular element of mesh is equal to 0.2 mm. For the mesh refinement, a smooth transition region has been considered around the probe measuring points and near the overlap ends. The discretization model of the double lap specimen consisted of 785,630 elements and 1,607,518 nodes. The GFRP elements have been modelled as linear elastic orthotropic materials, while the adhesive was modelled as being a linear elastic isotropic material.

5. Analytical Approach

The results and the conclusions obtained using the numerical method were verified with the existing analytical model, adequate for this type of joint configuration (Hart-Smith, 1973). The closed form solutions for the double lap joint specimen were obtained by applying the Hart-Smith model (Groll & Ţăranu, 2003; Hart-Smith, 1973). The latter is based on the Goland-Reisner algorithm (Goland & Reissner, 1944) and accounts for the adhesive plastic behavior. The maximum shear stress was computed using:

$$\zeta_0^{\text{ultim}} \approx \frac{\lambda P_k \gamma_f}{4}\left[\frac{\cosh(\lambda c)}{\sin(\lambda c)} + \Omega \frac{\sinh(\lambda c)}{\cosh(\lambda c)}\right], \tag{1}$$

where: $\lambda^2 = G_a / t_a \left(1/E_0 t_0 + 2/E_i t_i\right)$; P_k – tensile force per width unit; Ω – maximum value between [(1-Ψ)/(1+Ψ) or (Ψ-1)/(1+Ψ)]; $\Psi = E_i t_i / 2E_0 t_0$; G_a – modulus of elasticity in shear of the adhesive, [N/mm^2]; E_i – modulus of elasticity of the inner adherent, [N/mm^2]; E_0 – modulus of elasticity of the outer adherents, [N/mm^2]; t_0 – thickness of the outer adherents, [mm]; t_i – thickness of the inner adherent, [mm]; c – L/2, [mm]; L – overlap length, [mm].

The maximum peel stress was computed using:

$$\sigma_0^{\text{ultim}} \approx \zeta_0^{\text{ultim}} \left(\frac{3E_a^{'} t_a (1-\upsilon^2) t_0}{E_0 t_a}\right)^{\frac{1}{4}}, \tag{2}$$

where: E_a – the effective transversal elasticity modulus of the adherents, [N/mm^2]; υ – Poisson's coefficient for the adherents; t_a – the adhesive layer thickness, [mm].

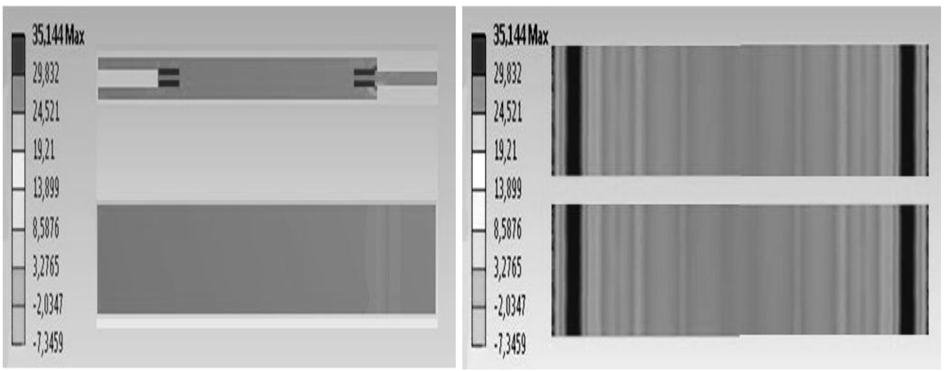
6. Results

The numerical analysis of the double lap joint showed that the adhesives layers are predominantly loaded in shear over the bond lengths. However, significant concentrations of peel stresses are located at the edges of the bonding region.

Since the bond length of the double lap joint is greater that the effective one predicted by the Hart-Smith model, the full-range behaviour of the joint could be investigated in the numerical analysis by recording the variations in the measuring points. For each set of three transverse, consecutive probe measuring points, the average value was computed. Thus, two sets of twelve design values for the specific points denoted with M1,…,M12; M1',…,M12' (Fig. 2) were determined in this manner. Using the design values, the distributions of the stresses within the overlap area were graphically represented (Figs. 6, 8).

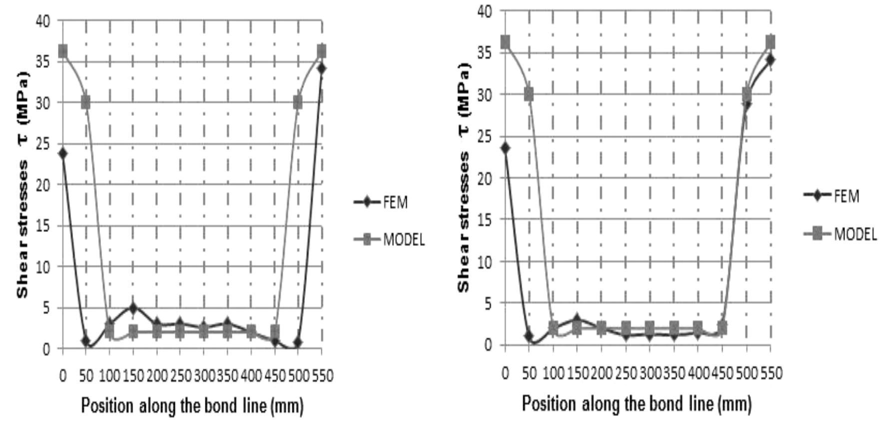
The shear stress and the peeling stress along the bond length have been also evaluated based on the Hart-Smith model and the values computed for the specific points were compared to the ones obtained through the numerical approach. For both overlap areas, the results obtained through the numerical method and analytical approach are in good agreement (Figs. 6, 8).

The shear stress map of the specimen loaded by a tensile force of 100kN is presented in Fig. 5 *a*. The shear stress distribution across the overlap surfaces is presented in Fig. 5 *b*. The analogy between the shear stress distributions computed through the analytical and numerical methods are graphically represented in Fig. 6 *a*, *b*.



a *b*

Fig. 5 – Shear stress distribution in: *a* – the double lap joint; *b* – overlap surface [MPa].

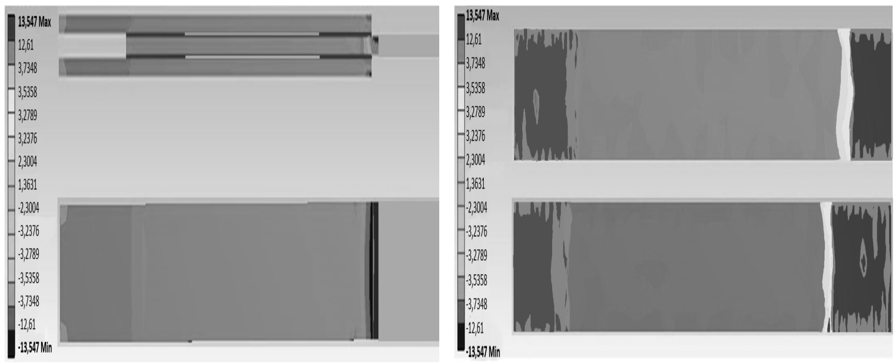


a *b*

Fig. 6 – Comparison between analytical and numerical results of shear stress distribution in the double lap joint: *a* – the upper adhesive layer; *b* – the lower adhesive layer.

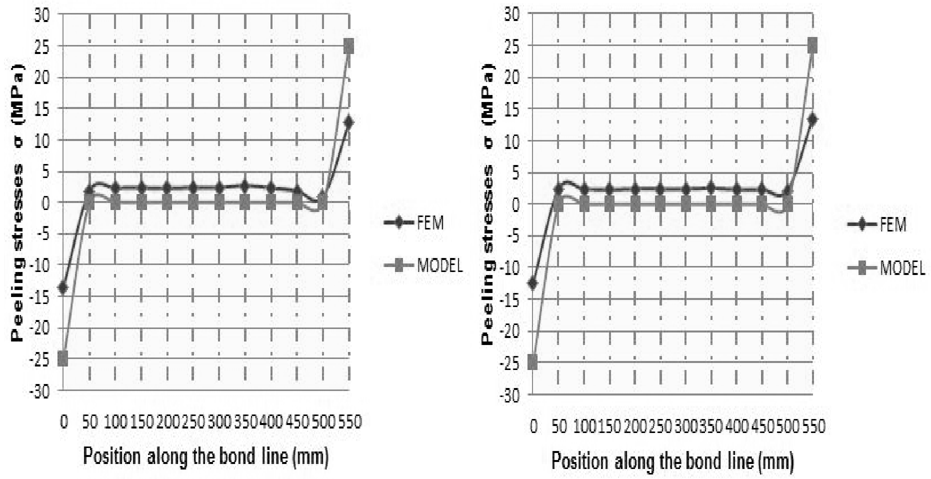
The investigation of the peel stresses distribution in the adhesive layers shows that the direction of the stresses changes as the distance from GFRP composite element end is increased. The total peeling force along the bond line is zero since the peel stresses are self-balancing.

The peeling stress map of the specimen acted by a tensile force of 100kN is presented in Fig. 7 *a*. The peeling stress distribution across the overlap surfaces is presented in Fig. 7 *b*. The analogy between the peel stress distributions computed through the analytical and numerical methods are graphically represented in Fig. 8 *a*, *b*.



a *b*

Fig. 7 – Peeling stress distribution in: *a* – the double lap joint; *b* – overlap surface, [MPa].



a *b*

Fig. 8 – Peel stress distribution in: *a* – the upper adhesive layer; *b* – the lower adhesive layer; of the double lap joint. Comparison between analytical and numerical results.

The results obtained through the numerical modelling of the double lap specimen are in good agreement with the results determined through similar numerical and experimental studies conducted on comparable joint configurations and constitutive materials (Keller & Valee, 2005a, b; Valee & Keller, 2006; Valee *et al.*, 2006). Furthermore, the patterns of the graphical representations for the shear stresses and normal stresses variation over the bond line area are very much the same with the ones obtained through the previously quoted studies.

7. Conclusions

A good agreement was obtained between the results determined through the analytical and the numerical analysis. The structural analysis of the model showed that the adhesives layers are predominantly loaded in shear over the overlaps lengths and significant peel stress concentrations tends to be formed near the overlap ends.

The shear stress distribution computed through the analytical approach diverge by less than 7.9% (upper overlap) and 8.1% (lower overlap) from the numerical results. However, the Hart-Smith double lap model overestimates the ultimate values of the peel stresses with approximately 44%, when compared to the FEA.

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RĂSPUNSUL STRUCTURAL LA FORFECARE AL ÎMBINĂRILOR ADEZIVE PRIN DUBLĂ SUPRAPUNERE A UNOR ELEMENTE PULTRUDATE DIN MATERIALE COMPOZITE

(Rezumat)

Se prezintă rezultatele pe modele analitice şi prin modelare numerica pe baza metodei cu elemente finite a unei îmbinări adezive realizate prin dublă suprapunere.

Îmbinarea este alcătuită din profile compozite polimerice armate cu fibre de sticlă (CPAFS) îmbinate cu ajutorul unui adeziv structural epoxidic. Pentru o evaluare detaliata a variațiilor tensiunilor de-a lungul straturilor de adeziv, 72 de puncte specifice de monitorizare au fost atribuite modelului numeric.

Variația tensiunilor tangențiale şi a tensiunilor normale de dezlipire de-a lungul lungimii de suprapunere este reprezentată grafic. Analiza valorilor ultime ale tensiunilor şi aliura graficelor de distribuție ale acestora, indică o bună corelare între rezultatele obținute pe cale numerică şi cele obținute analitic. Excepție fac valorile ultime ale tensiunilor normale înregistrate în apropierea marginilor libere ale lungimii de suprapunere.